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Effects of crown rot severity caused by *Fusarium culmorum* on agronomic performance of wheat genotypes

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Abstract

Global climate change, characterized by extreme temperatures, drought, and irregular precipitation, has intensified environmental stress conditions. In Middle Anatolia, harsh ecological conditions and monoculture-based agricultural practices further increase the incidence and severity of fungal diseases. The study aimed to determine the effects of crown rot disease on the grain yield and some agronomic characteristics of bread wheat cultivars. The experiments were conducted during the 2024-25 growing season in Yozgat and Yerköy locations, using 35 registered bread wheat cultivars, in a randomized block design and with three replications. *Fusarium culmorum* inoculation was applied twice under field and pot conditions; first on the seeds just before planting, second stem elongation stage using the grain colonization method. Bread wheat cultivars showed disease severity ranging from 6.3 to 54.2% under field conditions and 16.4–82.7% under pot conditions. Under field conditions, *Fusarium culmorum* inoculation caused 9.3% loss in plant numbers in the plot during the post-emergence period and 11.3% loss during the post-winter period, as well as an average reduction of 6.2% in plant height, 5.3% in thousand-kernel weight, and 17.9% in grain yield. In the pot experiment, *Fusarium culmorum* inoculation resulted decrease in flag leaf chlorophyll content (5.4%), plant height (5.8%), and grain yield (7.8%). The total physiological stress caused by fungal inoculation on the wheat cultivars studied was assessed by spike yield. A standardized yield value was then calculated for all spikes using a formula developed. Based on the standardized yield, 77.8% and 42.1% yield reduction was noted in inoculated spikes under field and pot conditions, respectively. These results indicate that crown rot disease poses a serious risk to wheat production. Therefore, developing strategies to prevent the disease and the losses it causes, especially the breeding of resistant varieties, is of great importance.

Keywords Root collar rot, Spike yield, Semi-arid condition, Biotic and abiotic stress, *Triticum aestivum*

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Introduction

Global food demand continues to rise, and agricultural production capacities and opportunities face serious challenges [1]. Pressures exerted by climate change and incorrect agronomic practices on environmental and biological systems increasingly threaten agriculture and food supply security [2]. The United Nations Food and Agriculture Organization has reported that global food production needs to increase by 70% by 2050 to feed the growing world population. Ensuring the sustainable production and increased efficiency of staple crops is critically important for food supply security in the face of climate change [3, 4]. In this context, an increase in the production of wheat (*Triticum aestivum* L.), which is vital crop for global food security, is of significant importance [5]. Wheat, is the primary food source for 40% of the world's population [6], is the most important staple cereal crop in temperate regions [7] with total of 798.5 million tonnes production on 219.5 million hectares over 120 countries [8]. Moreover, it is experiencing increasing demand in countries with rising urbanization and industrialization. In addition to being a rich source of starch and energy, wheat is an important component of a healthy diet due to its protein, vitamins, dietary fiber, and phytochemicals [9]. The global importance of wheat, its role in human and animal nutrition, and its contribution to the economy are undeniable [7]. Although wheat is the third most important crop in global production after maize and rice, its global distribution is much wider [8]. It can be successfully grown in a wide area between 60° N and 40° S latitudes and under very different altitude and climatic conditions [10, 11]. The Fertile Crescent is considered the origin of wheat domestication, and southeastern of Türkiye lies within this crescent [12]. Wheat is one of the most fundamental strategic food products within Türkiye. Türkiye ranked among the top 10 producers, contributing 2.8% to global wheat production with 22.0 million tons in 2023 [8]. However, global warming and associated climate changes can threaten wheat yield and food security, leading to an increase in disease problems within wheat ecosystems [3, 13]. In addition to direct effects on agriculture, climate has very strong indirect effects by influencing characteristics that determine plant development, such as soil biota, diseases, and pests [2, 14]. Yield and quality losses experienced in agriculture are also largely due to diseases and pests [3]. Consequently, climatic problems may lead to much more intense threats in the field of plant health in the future.

Wheat production is exposed to various biotic and abiotic stress factors. Among biotic stresses, pathogenic fungal diseases are among the most significant problems affecting wheat yield [15]. Root rot, crown rot, leaf spot or blight diseases and head blight are important fungal diseases that globally affect wheat and other cereals [16–18]. Crown rot damages wheat tissues, causing browning, decay, and impaired water and nutrient uptake. The severity of the disease increases late in the season, especially in warmer climates, severely affecting the transport of water and nutrients, leading to the characteristic "white head" appearance in plants [19, 20]. Crown rot is caused by fungal species in the genus *Fusarium*. Among these, *F. culmorum*, *F. graminearum*, and *F. pseudograminearum* are dominant [21]. These three species are particularly effective in wheat and have been reported to be responsible for significant yield losses in Türkiye, as well as in Egypt, Tunisia, Morocco, Algeria in the Mediterranean basin, and also in Australia, USA, and Canada [22–24]. The geographical distributions of these three species appear to be related to temperature and humidity [25]. *F. culmorum*, is the most virulent, is mostly found in cold and semi-humid climatic regions such as Western Europe. In contrast, *F. graminearum* and *F. pseudograminearum* are found in warmer and more humid climatic regions of the world, such as North America, Eastern Europe, Australia, and Southern China [20, 26]. Fusarium Crown Rot (FCR) poses a significant threat to wheat yield, especially under arid and semi-arid conditions, as stressed plants show greater susceptibility to the pathogen [23]. In Australia's wheat-growing regions, FCR causes yield losses ranging from 10% to 35% in areas with moderate infection, and over 50% in severe cases [20]. Furthermore, yield losses of up to 35% due to FCR have been reported in winter wheat in the Pacific Northwest of the United States [19]. In China, annual yield losses due to FCR are estimated to range between 10% and 30% [27].

Wheat production in Türkiye is mostly concentrated in arid and semi-arid areas in the central and southeastern regions, which makes wheat susceptible to FCR disease. It has been reported that the incidence of root and crown diseases in winter cereals, especially wheat, is 36% in Türkiye, and yield loss due to FCR has reached 43% [21]. FCR can be observed in all stages of wheat vegetation, from germination to maturity [28]. These pathogens cause various necrotic lesions in the tissues of roots, crowns, stems, and spikes. In Türkiye, particularly *Fusarium culmorum* and *F. graminearum* are highly significant pathogens responsible for FCR disease in wheat. Among FCR disease agents, *F. culmorum* is the most virulent in Türkiye, as well as globally [28, 29]. Low humidity, cold and semi-arid climate conditions required for *F. culmorum* infection are dominant in Türkiye's wheat growing zone, making *F. culmorum* one of the most important problems in wheat [23], as a matter of fact, *F. culmorum* is the FCR disease agent that is much more common than *F. graminearum* and *F. pseudograminearum* [6]. Traditionally, *F. culmorum* is known to be a trigger for FCR in cold and semi-arid climate regions. Indeed, *F. culmorum*

has been reported as the primary causal agent of root and crown rot, as well as head blight diseases, in wheat fields in Türkiye's Eastern Anatolia and Thrace regions [30]. However, it has been reported that *F. culmorum* has the highest isolation frequency as an FCR disease agent in Türkiye's Mediterranean region, followed by the Southeastern Anatolia, Central Anatolian Plateau, Aegean, Marmara, and Black Sea regions, respectively [22]. The high density seen especially in the Mediterranean Region having high moisture content is a paradox. This can be explained by changes in climatic factors such as relative humidity, temperature, and precipitation over the last 20 years, which affect the predisposition to *F. culmorum*-induced FCR disease [29].

In recent years, a significant increase in FCR diseases has been observed in winter wheat areas in Türkiye. This increase is particularly evident in the Central Anatolian Plateau and Thrace, Türkiye's primary winter wheat growing areas. In addition to the fluctuation in the incidence and severity of FCR, the dominance of *F. culmorum* has been steadily increasing from year to year [31, 32]. The rapid spread of FCR in these regions can be attributed to climate change, as well as to improper agricultural practices such as stubble management and soil tillage [25]. Plant residues in the soil are an important factor in the accumulation of *F. culmorum* inoculum (conidia/chlamydospores) [25]. On the other hand, this increase may also be related to the gradual adaptation of *F. culmorum* to warmer climates as a result of genome plasticity or to the increase in average temperatures caused by climate change [29].

FCR management strategies in wheat production include practices such as taking into account ecology and variety suitability regulating growing conditions, agronomic operations, and variety breeding. Although developing resistant varieties appears to be the most sustainable method for FCR control, the diversity of pathogens causing FCR, along with their distributions affected by climate and agricultural practices, further complicates disease control strategies [20]. Additionally, identifying resistant wheat varieties is challenging due to the genetic diversity of pathogens and complex field interactions. However, combining multiple control methods increases the effectiveness of FCR control. Sustainable control strategies include the integration of resistant variety use, optimum chemical and biological control methods, appropriate agronomic practices, and harvesting techniques [26, 33].

In recent years, the number of bread wheat varieties registered in Türkiye has increased. Accordingly, the varieties cultivated have changed considerably over the past decade. Although the general agronomic characteristics of these varieties are known, information regarding their responses to diseases is quite limited. In Türkiye, the status of agronomic traits and the total yield loss in these varieties, depending on the severity of Fusarium crown rot (FCR) caused by *F. culmorum*, are not yet fully understood. Therefore, the objectives of this study include (i) evaluating the current resistance status of wheat cultivars against *F. culmorum* and (ii) determining the effect of *F. culmorum*-induced FCR disease on yield in wheat. Furthermore, the methodological framework established to quantify the impact of disease severity on spike yield enhances the originality of this study by providing an objective and direct evaluation of disease-induced effects. Due to the importance of wheat in human nutrition, the results of this study are expected to have broad impact and contribute to the United Nations Sustainable Development Goals, such as "ending hunger, ensuring food security, improving nutrition, and promoting sustainable agriculture."

Materials and methods

Description of the study area and meteorological data

This study was carried out in two ecologically different environments: field and pot. Field experiment was conducted at the Yozgat Bozok University Agricultural Application and Research Center in Yerköy district of Yozgat province, while pot experiments were carried out in central Yozgat during the 2024-25 growing period. The altitude of the Yerköy trial area (39°38'47" N, 34°30'00" E) is 802 m, while that of Yozgat (39°46'20" N, 34°48'13" E), where the pot trial was conducted, is 1352 m. According to the soil analyses conducted, the soil properties of Yerköy were determined as loamy texture, slightly alkaline (pH 7.7), salt-free (0.02%), medium calcareous ($CaCO_3$ 8.0%), medium organic matter (2.0%), low available phosphorus (74 kg ha^{-1} P_2O_5), and very high available potassium (2265 kg ha^{-1} K_2O). To ensure compatibility of the soil used in the pot and field trials, the soil used in the pot trials was supplied from the Yerköy trial area.

In Yozgat, monthly average temperatures were below the long-term average in November and February, while they were above the long-term average in the other months of the study period (Table 1) [34]. At the Yerköy location, average monthly temperatures were below the long-term average in February and April, while in other months they were equivalent to or generally above the long-term average. April, one of the critical and important months in cereal cultivation, noted extremely low temperatures of -10.4 °C in Yozgat and – 6.7 °C in Yerköy. At both locations, precipitation has been below the long-term average in all months except April. Relative humidity was low in March, May, June, and July, and relatively high in other months in Yozgat. However, Yerköy has above-average relative humidity in January and April, while other months have below-average relative humidity.

Table 1 Meteorological data for the 2024-25 growing season of Yozgat and Yerköy

Year & Month		Temperature (°C)				Precipitation (mm)		Relative humidity (%)	
		Average	Min.	Max.	Long-term Average[1]	Monthly total	Long-term average	Monthly average	Long-term average
The Central District of Yozgat									
2024	November	4.6	-9.3	18.2	5.2	44.4	57.0	75.5	71.8
	December	2.4	-6.4	13.1	1.0	49.4	75.3	84.0	78.4
2025	January	2.3	-5.5	13.4	-1.2	21.4	67.6	79.7	78.3
	February	-2.9	-15.5	10.6	0	30.2	54.6	77.9	74.7
	March	7.3	-7.7	24.1	3.6	19.6	74.0	57.4	70.3
	April	7.3	-10.4	21.9	8.9	85.8	58.4	74.7	64.7
	May	14.4	2.3	29.6	13.3	47.6	67.9	58.3	64.8
	June	17.6	7.0	30.1	17.3	13.2	48.3	49.9	62.8
	July	23.0	8.3	39.0	20.3	1.0	14.2	43.8	57.2
The Yerköy District of Yozgat									
2024	November	7.5	-5.3	21.6	7.5	17.4	32.4	62.0	63.9
	December	4.5	-4.7	17.3	2.5	23.0	32.8	73.6	74.9
2025	January	4.0	-2.9	15.1	0.4	16.2	35.0	74.5	73.9
	February	1.0	-9.3	13.2	2.4	23.2	24.0	63.6	66.3
	March	11.5	-3.4	28.2	6.7	14.4	41.2	44.7	58.0
	April	10.9	-6.7	25.8	12.0	45.4	26.7	60.8	53.8
	May	18.6	6.5	33.3	16.3	9.6	48.8	46.0	54.3
	June	21.9	11.2	34.3	20.5	12.2	37.4	38.3	49.9
	July	27.3	12.7	42.1	23.8	1.2	8.4	32.6	43.1

[1]The long-term climate data represent a 30-year average

Table 2 Bread wheat cultivars used in the experiments and some of their characteristics

Cultivar	Registration year[1]	Origin	Seasonal type	Cultivar	Registration year[1]	Origin	Seasonal type
1.Adali	2018	Türkiye	W	19.Lucilla	2017	Italy	A
2.Ahmetaga	2004	Türkiye	A	20.Maden	2016	Türkiye	W
3.Alp 1	2017	Türkiye	W	21.Meke	2020	Türkiye	W
4.Ayten Abla	2019	Türkiye	A	22.Michelangelo	2017	Italy	W
5.Bagira	2020	Rusia	W	23.NE06545	2020	USA	W
6.Bayraktar 2000	2000	Türkiye	W	24.Nogal	2023	France	W
7.Comert 2	2011	Türkiye	W	25.Rebelde	2017	Italy	W
8.Destan	2016	Türkiye	W	26.Reis	2016	Türkiye	W
9.Ekiz	2004	Türkiye	A	27.Rumeli	2012	Türkiye	W
10.Enola	2016	Bulgaria	W	28.Selamibey	2020	Türkiye	A
11.Esperia	2011	Italy	W	29.S. Odes'Ka	2008	Ukraine	W
12.Flamura 85	1999	Romania	W	30.Sanli	2016	Türkiye	A
13.Glosa	2014	Romania	W	31.Taner	2018	Türkiye	A
14.Halis	2018	Türkiye	A	32.Topkapi	2018	Austria	W
15.Ikizce 96	1996	Türkiye	A	33.Tosunbey	2004	Türkiye	A
16.Kenanbey	2009	Türkiye	W	34.Yavuz	2019	Türkiye	A
17.Konya 2002	2002	Türkiye	A	35.Zlatoglava	2017	Ukraine	W
18.K. Odes'Ka	2008	Ukraine	W				

[1]Year of registration of the cultivar in Türkiye, *W* Winter type, *A* Alternative type

Experimental plant materials

This study used 35 bread wheat cultivars registered in Türkiye. Some of the cultivars used are materials registered in other countries before Türkiye. The cultivars used in the study were registered in Türkiye between 1996 and 2023. Their names, registration dates, origins, and seasonal types are shown in Table 2. Experimental research and field studies on bread wheat (*Triticum aestivum* L.) were conducted at the Faculty of Agriculture, Yozgat Bozok University, in compliance with relevant institutional, national, and international guidelines and legislation. The plant materials used in this

study consisted of cultivated wheat cultivars and did not include any wild or endangered species. All plant materials were obtained from the seed collection of the Department of Field Crops, Faculty of Agriculture, Yozgat Bozok University.

Pathogen

The pathogen used in the study was isolated in May 2023 from wheat plants showing head blight symptoms in a field experiment at the Yerköy Research Station. Fungal isolation studies were carried out using traditional mycological procedures, and the single spore technique described by Endes et al. [35] was used for the purification of the obtained isolates. Pure isolates were first identified as *F. culmorum* (YBUFc-FHB) according to their morphological and cultural characteristics, using the diagnostic key described by Leslie and Summerell [36]. Upon examination of the colony morphology of *Fusarium culmorum* isolates, it was determined that colonies initially exhibited white growth; however, as the culture aged, the mycelial structure displayed a progressive color change ranging from light pink to dark pink. Macroconidia were observed to be short, slightly curved, and predominantly 4–6 septate. The dimensions of the macroconidia ranged from 15.3 to 60.4 µm × 3.4–5.7 µm, and they were produced abundantly. No microconidia were detected in the examined isolates. Chlamydospores were formed either singly or in pairs. Furthermore, chlamydospore development occurred relatively rapidly compared to other species, taking approximately 2–4 weeks to form. Pathogenicity tests were performed under climate room conditions (16 h: 8 h light: dark (photoperiod) under light intensity of 500 µmol m^{-2} s^{-1} at a temperature of 25 ± 1 °C with a relative humidity of 65% according to the pipette method described by Endes [37]. YBUFc-FHB was re-isolated from all wheat crown roots to fulfill Koch's postulates.

Genomic DNA of the YBUFc-FHB isolate, determined to have a very high virulence level, was extracted according to the method described by Endes and Kayım [38]. PCR analyses and electrophoresis of the YBUFc-FHB isolate were performed using protocols described by Endes [39]. The internal transcribed spacer (ITS) region of ribosomal DNA and the translation elongation factor 1-alpha (EF1-α) gene were amplified with ITS4/ITS5 and EF1/EF2 primer sets, respectively [18, 40]. The YBUFc-FHB sequence was deposited in the NCBI GenBank database (accession numbers: PX362956 and PX363521, respectively), and the pure isolate culture is preserved by freezing in 30% glycerol at -80 °C and – 20 °C for further studies [41].

Inoculum preparation and inoculation

YBUFc-FHB inoculum used in all experiments conducted in the greenhouse and field were obtained in two different ways for application to both wheat seeds and plants. The first method involved incubating YBUFc-FHB isolate cultures grown on potato dextrose agar (PDA) medium at 22 ± 1 °C for 20 days under an 8-hour fluorescent light and 16-hour dark light cycle, until the colony completely covered the Petri dish [35]. To harvest the conidia, 10 mL of sterile distilled water containing 0.01% Tween 80 was added to each Petri dish, and a sterile scalpel was used to transfer the conidia grown on the media into the water. Subsequently, the mycelia and conidia in slurry form were thoroughly crushed with a mortar and pestle, and the resulting suspension was filtered through a 2-layer cheesecloth. The concentration of the conidial suspension was adjusted to 1×10^6 conidia mL^{-1} for inoculation using a hemocytometer [41]. 100 seeds (3 × 100) of each wheat cultivar were transferred to an Erlenmeyer flask containing 200 mL of conidial suspension at a concentration of 1×10^6 conidia mL^{-1} [42]. The flasks were incubated with their mouths closed at room conditions on a digital orbital shaker at 120 rpm for one hours. At the end of this period, the conidial suspension in the flask was carefully discarded inside a sterile cabinet, and the flask containing only wheat seeds was incubated overnight in the cabinet. Thus, the moisture on the seeds was completely removed, leaving dry but inoculum-treated seeds. Subsequently, the wheat seeds were placed into sterile paper envelopes and used in field and greenhouse studies as ready for sowing.

The second inoculum was obtained by making minor modifications to the method described by Akgül and Erkilic [43]. The inoculum was prepared by colonizing YBUFc-FHB isolate on sorghum seeds boiled in water. For this purpose, sorghum grains were first washed in tap water to remove coarse debris, strained, and then dried on clean coarse filter papers before being filled halfway into autoclavable 2.5 L Erlenmeyer flasks. These flasks were then placed in an autoclave and sterilized at 121 °C and 1 atm pressure for 60 min. The autoclaving process was performed in duplicate. After autoclaving and once the grains had cooled sufficiently, 5 mm agar discs were cut from 5 to 6 days old fresh YBUFc-FHB cultures grown on PDA media in Petri dishes, and 8–10 of these discs were added to each flask to inoculate the grains. During the 20-day incubation period at 22 ± 1 °C, 250 mL of liquid potato dextrose broth (PDB) was added to each flask on the 6th and 13th days, and the grains in the flasks were shaken once every two days to ensure homogeneous colonization of all grains. At the end of the 20th day of incubation, all wheat grains were emptied from the flasks, aerated for 24 h in disinfected plastic trays within a sterile cabinet, and then 100 g was placed into sterile

paper envelopes and used in field studies as ready for sowing. The sorghum inoculum prepared in sterile paper envelopes was carefully poured onto the crown region of wheat plants during the stem elongation stage (Zadoks decimal code 35) in the cool evening, ensuring even distribution, and then the plants were irrigated for 4 h using the drip irrigation method. The irrigation process was repeated on the third, sixth, and ninth days.

Experimental design and applications

The field experiment was arranged in randomized block design with three replications. Each plot consisted of a single 1 m long row, and 100 viable seeds were planted in these rows. This procedure was valid for fungus-infected and control seeds of all cultivars. The experiment was sown in the first week of November, and fertilization was carried out with 23 kg ha^{-1} N and 60 kg ha^{-1} P_2O_5 at sowing and 40 kg ha^{-1} N during the tillering period. Weed control was done manually and irrigation was carried out using drip irrigation. Harvesting was done with a plot combine harvester in the second week of July.

Soil was obtained from the field where the Yerköy field experiment area was conducted for the pot experiment; after being sterilized at 180 °C for 8 h, it was placed in 4-liter pots. Planting was done with five plants per pot and three replications. The pots were kept under natural conditions and fertilized in a manner equivalent to field experiment conditions. When necessary, pots were moved to uncontrolled greenhouses to mitigate climatic risks (hail, storms, late spring frosts, etc.). Plants reaching harvest maturity were harvested and threshed individually by hand, and yield values per plant were determined using precision scales.

Observations, labeling of infected plants, and standardized spike yield

In the field trial, observations were the number of days to heading (from January 1), the first plant count after emergence (December 15), the second plant count after winter (March 5), plant height, grain yield, thousand-kernel weight, standardized spike yield, and disease severity. Chlorophyll content, number of days to heading, number of whiteheads, plant height, grain yield per plant, standardized spike yield, and disease severity were determined in the pot experiment.

The height at which necrotic tissues emerged from the root collar region up to the third node of the plant was used as the basis, and disease severity assessment was performed with minor modifications to the methods described by Wildermuth and McNamara [44] and Erginbas-Orakci et al. [45]. In here; 0: immune, 1: 1–9% resistant (R), 2: 10–25% moderately resistant (MR), 3: 26–50% moderately susceptible (MS), 4: 51–75% susceptible (S), 5: 76–100% highly susceptible (HS). The severity of the disease was calculated using the Towsend Hauberger formula and given as a percentage value.

According to the disease scale used in the study, evaluations were conducted on 10 cultivars in the field experiment, where plants representing all disease severity levels were present. In the pot experiment, however, assessments were carried out on 5 cultivars that also included plants representing all disease severity levels, due to the more limited number of plants compared to the field experiment. Then, three infected plants were labeled in each cultivar for each disease severity according to 0–5 scale [46] based on infection symptoms observed on the root collar and in the lower parts of the stem at heading and subsequent growth stages (Zadoks decimal code 50 and later stages). The spikes of the labeled plants were harvested and evaluated separately.

In order to determine the effect of disease-induced stress, total seed yields of the labeled spikes were determined and then; in order to facilitate comparison, a standardized yield value was created for each spike using the formulas (1 and 2) below.

$$\mathrm{SKW} = \mathrm{SY}/\mathrm{KN} \tag{1}$$

$$\mathrm{SSY} = \mathrm{SKW} \times 40 = (\mathrm{SY}/\mathrm{KN}) \times 40 \tag{2}$$

Here, SY represents the total kernel weight per spike (g), while KN denotes the total number of kernels per spike. To enable comparisons among spikes with different kernel numbers, the standardized spike yield (SSY) was calculated. SSY was obtained by multiplying the single kernel weight (SKW) by a fixed kernel number of 40 (Eq. 2). This approach allows spike yields to be compared on a standardized basis of 40 kernels.

Statistical analysis

The experimental data were examined using the analysis of variance (ANOVA) method in accordance with the randomized blocks design using the SAS software [47]. The means were compared using the Tukey's honest significant difference (HSD) at $\alpha = 0.05$.

Results

This study is based on experiments conducted under two different conditions during the 2024–2025 growing season. A high level of disease incidence was observed under both conditions. This indicates that the results reliably reflect the responses of bread wheat cultivars to FCR disease at high infection levels. Artificial inoculations resulted in severe FCR intensity and adversely affected agronomic traits. This demonstrates that the findings are sufficiently representative and reliable.

Field experiment

In the field experiment, the number of days to heading was determined according to the method specified by UPOV [48] as the time when the first spikelets were observed in 50% of the ears in the plot. Since no variation was observed between the control and fungus-infected plots, variance analysis was not performed (Table 3). The experiment average was 126.9 days, with the heading days of the cultivars varying between 122 and 131 days, and all cultivars completed heading within a 10-day time period.

Differences between control plots and plots inoculated with fungus in the first plant count (after emergence) and the second plant count (after winter) were found to be statistically significant. Variance analysis was performed separately for control and inoculation treatments (Table 3). In all the treatments, 100 viable seeds were sown. In this context, in the first count, the plant number

Table 3 Averages of the number of days to heading, plant count after emergence (1st count) and after winter (2nd count) and plant height for wheat cultivars under field conditions

Cultivar	Number of days to heading	Number of plants						Plant height (cm)		
		1st count			2nd count					
		C	FI	LPN (%)	C	FI	LPN (%)	C	FI	LPH (%)
1. Adali	125	70.7	68.3	-3.4	63.3	61.3	-3.2	71.1	70.8	-0.5
2. Ahmetaga	129	81.0	70.0	-13.6	71.0	59.0	-16.9	68.7	60.6	-11.7
3. Alp 1	128	83.0	77.3	- 6.9	71.7	69.7	-2.8	73.5	69.7	-5.2
4. Ayten Abla	123	88.3	77.0	-12.8	78.3	69.3	-11.5	62.7	58.8	-6.2
5. Bagira	127	81.0	75.3	-7.0	70.7	65.7	-7.1	65.9	58.4	-11.4
6. Bayraktar 2000	125	77.3	74.7	- 3.4	73.7	62.0	-15.9	70.0	66.9	-4.5
7. Comert 2	125	86.3	75.7	-12.3	77.7	65.0	-16.3	59.2	58.6	-1.0
8. Destan	128	81.0	74.3	-8.3	72.7	68.7	-5.5	71.9	68.0	-5.5
9. Ekiz	128	81.0	74.3	-8.3	75.7	63.7	-15.9	64.3	61.5	-4.4
10. Enola	122	68.3	65.0	-4.8	63.7	60.0	-5.8	55.5	52.7	-5.1
11. Esperia	127	81.7	80.3	-1.7	75.3	62.0	-17.7	64.3	65.6	+2.1
12. Flamura 85	126	83.0	28.7	-65.4	72.3	24.0	-66.8	61.1	59.0	-3.4
13. Glosa	126	82.0	75.7	-7.7	70.7	68.0	-3.8	65.4	61.7	-5.6
14. Halis	130	84.3	79.7	-5.5	76.7	66.3	-13.6	69.6	68.2	-1.9
15. Ikizce 96	128	78.0	70.7	-9.4	73.3	62.0	-15.4	68.4	63.1	-7.8
16. Kenanbey	130	82.0	79.7	-2.8	71.0	68.7	-3.2	77.5	66.4	-14.3
17. Konya 2002	125	94.3	82.3	-12.7	79.3	65.3	-17.7	66.4	61.0	-8.1
18. K. Odes'Ka	124	83.0	71.7	-13.6	74.3	65.7	-11.6	67.2	65.9	-1.9
19. Lucilla	128	67.0	61.0	-9.0	62.3	55.3	-11.2	54.3	51.2	-5.8
20. Maden	127	80.3	64.3	-19.9	71.0	47.3	-33.4	62.5	60.1	-3.9
21. Meke	123	84.0	79.3	-5.6	69.3	67.7	-2.3	76.1	72.5	-4.8
22. Michelangelo	129	87.7	89.3	+1.8	72.7	73.7	+1.4	66.5	58.0	-12.8
23. NE06545	128	88.3	75.7	-14.3	74.3	67.3	-9.4	64.5	58.5	-9.3
24. Nogal	128	88.3	80.3	-9.1	72.7	62.7	-13.8	61.4	57.9	-5.7
25. Rebelde	128	84.3	75.0	-11.0	70.7	65.3	-7.6	66.3	66.2	-0.2
26. Reis	127	85.7	82.3	-4.0	67.7	71.7	+5.9	76.9	68.8	-10.5
27. Rumeli	128	84.0	79.0	-6.0	63.3	59.7	-5.7	66.7	61.5	-7.7
28. Selamibey	127	83.0	83.7	+0.8	71.0	66.3	-6.6	69.9	65.3	-6.6
29. S. Odes'Ka	124	76.3	67.7	-11.3	71.3	58.7	-17.7	64.8	59.7	-7.8
30. Sanli	128	81.0	80.3	-0.9	71.7	69.0	-3.8	72.5	66.1	-8.7
31. Taner	130	76.0	73.7	-3.0	70.0	61.7	-11.9	90.4	83.1	-8.0
32. Topkapi	131	65.3	61.7	-5.5	58.7	57.7	-1.7	68.8	67.0	-2.7
33. Tosunbey	127	84.0	75.0	-10.7	74.0	64.7	-12.6	71.3	66.1	-7.2
34. Yavuz	123	87.3	79.3	-9.2	74.7	73.7	-1.3	76.0	72.1	-5.0
35. Zlatoglava	129	78.3	72.3	-7.7	73.7	65.0	-11.8	64.7	56.5	-12.6
Mean	126.9	81.4	73.7	-9.3	71.4	63.2	-11.3	67.9	63.6	-6.2
F		**	**		*	**		**	**	
CV(%)		8.2	11.1		8.7	12.1		2.2	2.6	
HSD		21.9	26.7		20.3	25.1		4.9	5.4	

CV Coefficient of variation, **Significant at $p < 0.01$, *Significant at $p < 0.05$, C Control, FI Fungus-infected, LPN Loss in plant numbers, LPH Loss of plant height, HSD Tukey's honest significant difference ($\alpha = 0.05$)

for cultivars was between 65.3 and 94.3, with the average of 81.4. in control plots. This number was between 28.7 and 89.3 plants for inoculated plots. The overall average for the cultivars in the plots where fungal inoculation applied was 73.7, indicating a 9.3% loss in plant count compared to the control. When the effect of inoculation on plant numbers is considered on a cultivar basis, the result observed in cv. Flamura 85 is striking. While plant emergence of cv. Flamura 85 was 83.0 in the control plots, it decreased sharply to 28.7 after fungal inoculation. In this respect, it stands out as the cultivar that most significantly lowers the overall average.

In the second plant count, the average number of plants in the control plots was 71.4, while it was 63.2 in the fungal inoculation performed plots. These values indicate that fungus-infection result in average 11.3% decrease in plant emergence compared to the control plots. On the other hand, compared to the first plant count, the average plant number in the second count decreased by an average of 9.9% among control plots and by an average of 10.5% among fungus-infected plots.

Differences between cultivars in plant height were statistically significant ($p < 0.01$) in the control and fungus-infected plots (Table 3). Fungal infection caused an average 6.2% reduction in plant height across cultivars. This reduction reached its highest value (14.3%) in the cv. Kenanbey. In contrast, a 2.1% increase was recorded in the cv. Esperia. Plant height remained virtually unchanged in the cvs. Adali and Rebelde.

The differences in grain yields between genotypes were found to be statistically significant ($p < 0.01$). In the control plots, grain yields of the cultivars ranged from 265.2 to 505.9 g m^{-2}, while in the fungus-infected plots, they ranged from 182.8 to 459.7 g m^{-2} (Table 4). The average grain yield was determined as 340.4 g m^{-2} in the control plots, while it was recorded as 17.9% lower and 281.0 g m^{-2} in the fungus-infected plots. The loss rate for the cvs. Michelangelo, Esperia, and Sanli was below 5%, while the loss rate for the cvs. Flamura 85, Konya 2002, and Syrena Odes'Ka was found to be 30% or higher.

In Table 4, the mean yields under control conditions demonstrate differences in the yield performance of the genotypes. Under fungal-inoculated conditions, cvs. Esperia, Yavuz, and Glosa were located in the highest-yielding statistical group (459.7, 414.1, and 409.4, respectively). The same cultivars were also among the highest-yielding under control conditions. Disease severity and yield loss were 6.3% and 2.0% in Esperia, 26.7% and 10.3% in Yavuz, and 48.7% and 19.1% in Glosa, respectively. These findings indicate a strong relationship between disease severity and yield loss.

As a result of inoculation of seed and plant with *F. culmorum*, disease severity was observed in 35 cultivars at rates ranging from 6.3% to 54.2%, depending on the level of infection and the extent of disease progression in the stems (tissue discoloration). Disease severity was determined to be over 50% in two cultivars, 41–50% in five cultivars, 31–40% in ten cultivars, 21–30% in nine cultivars, 11–20% in eight cultivars, and below 10% in one cultivar. In the evaluation based on this grouping, the average losses in grain yield were found to be 27.1%, 25.6%, 20.7%, 16.2%, 11.0%, and 2.0%, respectively.

The average thousand-kernel weight of the cultivars varied between 24.9 and 35.2 g in the control plots and between 23.5 and 34.1 g in the fungus-infected plots. In the fungus-infected plots, thousand-kernel weight decreased by an average of 5.3% compared to the control plots. The loss in thousand-kernel weight due to fungus infection was over 10% in the cvs. Comert 2, Syrena Odes'Ka, Bagira, and Zlatoglava, but less than 2% in the cvs. Bayraktar 2000, Selamibey, Rebelde, and Alp 1. In contrast, there was an increase between 1.0% and 5.3% in the fungal-infected plots of cvs. Halis, Michelangelo, Sanli and Destan.

To examine the effect of physiological problems caused by infection in plants on spike yield, standardized spike yields obtained from labeled spikes belonging 10 cultivars are presented in Table 5. Cultivar, disease severity, and cultivar × disease severity interaction were found to be significant ($p < 0.01$) on grain yield per spike. The average grain yields at the six disease severity levels (0–5) were statistically different. Average grain yields over the cultivars decreased steadily with increasing disease severity, and compared to the control, the loss was 9.4% at the first severity level, reaching 77.8% at the fifth severity level. The reducing effect on disease severity was seen in all cultivars, but the reduction rates differed. When examining the average values of genotypes according to disease severity, a loss rate of 58.6% was observed for the cv. Konya 2002 between healthy and 5 disease severity levels, while this rate was 87.4% for the cv. Ahmetaga. Figure 1 shows the appearance and weights of grains obtained from spikes at different severity degree (from 0 to 5). As the severity of the disease increases, problems arise in grain filling and even grain formation.

Pot experiment

Statistically significant ($p < 0.01$) differences were found between the chlorophyll content values of the cultivars in the control and fungus-infected plots. The average chlorophyll content in the control plots ranged from 51.1 (cv. Lucilla) to 65.2 spad (cv. Maden), while in the fungus-infected plots it ranged from 50.1 (cv. Sanli) to 62.1 spad (cv. Yavuz) (Table 6). In both the control and fungus-infected plots, the cultivars showed distribution across five statistical groups. An average of 5.4% decrease in chlorophyll content was observed in fungus-infected plots compared to control plots. This decrease

Table 4 Effects of crown rot disease on grain yield, thousand-kernel weight, and disease severity of cultivars under field conditions

Cultivar	Grain yield			Thousand-kernel weight			Severity of disease (%)
	C (g m^{-2})	FI (g m^{-2})	LGY (%)	C (g)	FI (g)	LTKW (%)	
1. Adali	402.3	341.3	-15.2	27.9	27.0	-3.2	18.5
2. Ahmetaga	283.4	257.6	-9.1	29.4	28.0	-4.9	19.5
3. Alp 1	298.3	262.2	-12.1	30.4	29.8	-1.9	26.7
4. Ayten Abla	279.4	234.1	-16.2	24.9	24.1	-3.2	33.8
5. Bagira	360.7	261.5	-27.5	30.4	27.0	-11.1	42.0
6. Bayraktar 2000	323.5	279.4	-13.6	30.8	30.7	-0.3	10.2
7. Comert 2	278.6	239.2	-14.1	32.3	27.7	-14.4	25.2
8. Destan	323.0	298.8	-7.5	32.4	34.1	+5.3	33.0
9. Ekiz	275.0	226.5	-17.6	31.2	29.7	-5.1	33.3
10. Enola	284.6	206.4	-27.5	33.8	30.8	-8.9	26.5
11. Esperia	469.3	459.7	-2.0	33.2	32.1	-3.3	6.3
12. Flamura 85	292.3	182.8	-37.5	32.3	30.7	-5.0	31.9
13. Glosa	505.9	409.4	-19.1	31.6	29.0	-8.2	48.7
14. Halis	361.8	335.6	-7.2	33.7	34.1	+1.0	22.6
15. Ikizce 96	294.4	225.4	-23.4	29.4	27.3	-6.9	27.3
16. Kenanbey	296.5	242.7	-18.2	33.6	32.7	-2.8	35.9
17. Konya 2002	265.2	185.4	-30.1	33.6	30.8	-8.6	50.2
18. K. Odes'Ka	392.6	303.8	-22.6	32.8	31.1	-5.2	31.2
19. Lucilla	295.3	231.0	-21.8	29.8	26.9	-9.8	32.3
20. Maden	396.5	327.6	-17.4	33.3	32.0	-3.9	31.0
21. Meke	394.1	308.6	-21.7	34.1	31.8	-6.6	34.3
22. Michelangelo	323.4	318.5	-1.5	30.1	30.6	+1.6	18.4
23. NE06545	315.1	272.8	-13.4	25.8	23.5	-9.0	15.8
24. Nogal	396.8	331.9	-16.4	28.0	26.2	-6.5	11.5
25. Rebelde	365.7	311.3	-14.9	26.6	26.1	-1.9	17.1
26. Reis	334.8	247.5	-26.1	32.9	31.3	-5.0	39.4
27. Rumeli	346.5	263.0	-24.1	32.8	30.4	-7.3	54.2
28. Selamibey	335.4	290.1	-13.5	30.0	29.6	-1.3	21.6
29. S. Odes'Ka	276.3	193.3	-30.0	35.2	30.8	-12.7	46.4
30. Sanli	343.5	329.3	-4.1	29.8	30.5	+2.2	19.0
31. Taner	362.7	263.6	-27.3	32.6	29.6	-9.3	47.8
32. Topkapi	296.3	241.9	-18.4	31.0	29.3	-5.5	27.8
33. Tosunbey	409.0	330.1	-19.3	33.1	30.1	-8.9	25.5
34. Yavuz	461.7	414.1	-10.3	32.1	30.0	-6.4	26.7
35. Zlatoglava	274.8	208.3	-24.2	30.8	27.6	-10.2	47.3
Mean	340.4	281.0	-17.9	31.2	29.5	-5.3	29.7
F	**	**		**	**		
CV (%)	10.2	11.3		3.7	3.6		
HSD	113.3	103.4		3.7	3.5		

CV Coefficient of variation, ** Significant at $p < 0.01$, *C* Control, *FI* Fungus-infected, *LGY* Loss of grain yield, *LTKW* Loss of thousand kernel weight, HSD Tukey's honest significant difference ($\alpha = 0.05$)

was particularly high (11.2–12.9%) in the cvs. Destan, Rebelde, and Reis. However, increases ranging from 0.2 to 6.1% were recorded in some cultivars, such as cvs. Ahmetaga, Ekiz, Lucilla and Yavuz.

The number of days to heading varied between 130 and 141 days for the 35 cultivars with the average of 138.1 days (Table 6). Cv. Bayraktar 2000 was the earliest, while cvs. Ekiz and Halis were the latest. In the pot experiment, "white head" formation was observed in the pots of 16 cultivars infected with the fungus; the highest number of white heads was observed in cv. Ikizce 96, followed by cvs. Comert 2, Taner, and Enola. In the control treatment, no white head formation was observed in any cultivar.

Over the cultivars, plant height varied between 60.1 and 95.4 cm in the control plots and it averaged 77.3 cm. The cultivars were distributed across 11 statistical groups, with cvs. Kenanbey and Taner identified as the longest cultivars. Cvs. Flamura 85, Rebelde, Nogal, Esperia, and Comert 2 had the shortest plant height values. In the fungus-infected plots, the longest plant height was again observed in the cvs. Kenanbey and Taner, as in the control plots. Cvs. Rebelde, Comert 2, Esperia, and

Table 5 Effect of crown rot disease severity on standardized grain yield of per spike under field conditions (g spike^{-1})

Cultivar	Severity of disease						Mean
	0	1	2	3	4	5	
Adali	0.945	0.968	0.896	0.593	0.442	0.163	0.668 ef
Ahmetaga	1.188	0.987	0.877	0.570	0.608	0.150	0.730 de
Alp 1	1.151	1.030	1.050	0.961	0.338	0.211	0.790 cd
Ayten Abla	1.188	1.032	0.979	0.851	0.693	0.281	0.837 bc
Comert 2	0.810	0.838	0.747	0.676	0.369	0.112	0.592 f
Enola	1.368	1.310	1.228	0.768	0.526	0.382	0.930 a
Konya 2002	1.141	0.960	0.968	0.700	0.567	0.472	0.801 bcd
Reis	1.357	1.370	1.152	0.755	0.592	0.357	0.931 a
Taner	1.281	1.011	1.021	0.878	0.553	0.291	0.839 bc
Tosunbey	1.254	1.075	0.983	0.968	0.822	0.177	0.880 ab
Mean	1.168 A	1.058 B	0.990 C	0.772 D	0.551 E	0.260 F	0.800
Loss (%)	0	-9.4	-15.2	-33.9	-52.8	-77.8	

Coefficient of variation: 10.3, Tukey's honest significant difference ($HSD_{\alpha:0.05}$) for disease severity: 0.062, $HSD_{\alpha:0.05}$ for cultivars: 0.089, $HSD_{\alpha:0.05}$ for cultivar× disease severity: 0.048



Fig. 1 Appearance of grains from spikes at different severity degree. Respectively, (**a**) healthy, (**b**) severity degree 1, (**c**) severity degree 2, (**d**) severity degree 3, (**e**) severity degree 4, and (**f**) severity degree 5. (Bar = 10 mm)

Nogal showed the shortest plant height values. On average across cultivars, fungal infection caused a 5.8% loss in plant height. Contrastingly, cvs. Destan, Bagira, and Glosa in the fungus-infected plots exhibited plant heights 0.7–2.6% longer than the control plots. Cvs. Meke and Selamibey showed a decrease in plant height of over 10% compared to the control averages.

The effect of cultivar on grain yield per plant obtained in the pot environment was significant ($p < 0.01$) in both control and fungus-infected treatments (Table 7).

Grain yield per plant of the cultivars varied between 2.698 and 5.824 g plant^{-1} in the control treatment and between 2.104 and 5.761 g plant^{-1} in the fungus-infected treatment. While the average grain yield of control plants was 4.013 g plant^{-1}, it was 3.703 g plant^{-1} in the fungus-infected treatment with a 7.8% loss. The highest loss in grain yield per plant was observed in the cv. Flamura 85, followed by the cvs. Comert 2, Zlatoglava, and Taner. The grain yields per plant in the fungus-infected pots of the cvs. Sanli, Destan, Glosa, Rebelde, Krasunia Odes'Ka, Reis, Maden, Lucilla, and Esperia were found to be higher than the control averages, varying between 0.8 and 6.6%. The severity of disease observed in the cultivars grown in fungus-infected pots was found to be significantly higher (16.4–82.7%) compared to the field experiment. When classified according to disease severity as over 61%, between 41 and 60%, and below 40%, yield loss relative to control pots was determined to be 12.2%, 10.8%, and 2.4%, respectively.

In the pot experiment, cultivars, disease severity, and cultivar × disease severity interaction were significant ($p < 0.01$) for the standardized spike yield obtained from labeled plants according to the severity of infection at the crown rot in five cultivars (Table 8). The average spike yields observed at different disease severity levels formed three statistically distinct groups. Compared to healthy plants (control), spike yield decreased in parallel with the disease severity; this decrease was recorded as 12.4% on average in the 1st severity and 42.1% in the 5th severity spikes. Three statistical groups were formed based on the standardized spike yield averages of the cultivars, and the cultivars showed spike yield averages ranging from 1.039 to 1.442 g spike^{-1}.

Field and pot experiments have demonstrated the effect of crown rot disease caused by *F. culmorum* is significant on examined agronomic characteristics of bread wheat cultivars. By labeling plants according to disease severity, the negative effects caused by *F. culmorum* on wheat plants could be demonstrated more objectively. In addition, from our observation on labeled plants, it was determined that the disease agent also caused deterioration and abnormalities in the spike structure. Figure 2 shows abnormalities in the spike structure of a labeled plant with a very high infection intensity at the root collar and above.

Table 6 Effects of crown rot disease on chlorophyll content, days to 50% heading, white head, and plant height in pot experiment

Cultivar	Chlorophyll content (Spad)			Number of days to heading	White head		Plant height (cm)		
	C	FI	DCC (%)		C	FI[1]	C	FI	LPH
1. Adali	58.3	53.9	-7.5	137	0	1	83.5	78.5	-6.0
2. Ahmetaga	57.8	57.9	+0.2	140	0	0	77.7	71.6	-7.9
3. Alp 1	61.4	59.4	-3.3	139	0	0	73.9	67.9	-8.1
4. Ayten Abla	55.8	54.0	-3.2	137	0	1	78.5	69.3	-11.7
5. Bagira	58.1	52.8	-9.1	138	0	2	73.4	74.6	+1.6
6. Bayraktar 2000	62.4	56.8	-9.0	130	0	0	75.1	70.2	-6.5
7. Comert 2	54.9	52.9	-3.6	139	0	4	60.1	58.7	-2.3
8. Destan	62.6	54.5	-12.9	139	0	1	72.3	74.9	+3.6
9. Ekiz	57.5	58.1	+1.0	141	0	0	82.4	76.9	-6.7
10. Enola	59.2	56.6	-4.4	134	0	4	73.6	68.7	-6.7
11. Esperia	59.2	57.8	-2.4	136	0	0	62.7	58.7	-6.4
12. Flamura 85	58.8	53.7	-8.7	140	0	0	69.8	66.6	-4.6
13. Glosa	60.1	57.7	-4.0	138	0	0	71.1	71.8	+1.0
14. Halis	60.8	58.8	-3.3	141	0	0	74.4	73.8	-0.8
15. Ikizce 96	61.4	57.1	-7.0	138	0	7	81.5	76.4	-6.3
16. Kenanbey	59.8	59.3	-0.8	137	0	0	79.9	78.1	-2.3
17. Konya 2002	59.9	57.9	-3.3	139	0	0	95.4	88.3	-7.4
18. K. Odes'Ka	58.8	53.4	-9.2	140	0	2	83.0	79.6	-4.1
19. Lucilla	51.1	54.2	+6.1	140	0	0	80.7	73.8	-8.6
20. Maden	65.2	59.2	-9.2	138	0	0	74.7	70.8	-5.2
21. Meke	59.8	57.0	-4.7	138	0	1	85.4	73.8	-13.6
22. Michelangelo	56.6	51.3	-9.4	138	0	1	82.1	75.5	-8.0
23. NE06545	63.7	59.2	-7.1	139	0	0	77.3	73.4	-5.0
24. Nogal	61.2	55.9	-8.7	138	0	1	63.1	55.0	-12.8
25. Rebelde	58.5	51.9	-11.3	139	0	0	66.9	61.6	-7.9
26. Reis	60.9	54.1	-11.2	140	0	1	81.4	75.6	-7.1
27. Rumeli	60.3	56.5	-6.3	137	0	0	78.6	78.0	-0.8
28. Selamibey	58.2	56.0	-3.8	137	0	2	73.5	70.0	-4.8
29. S. Odes'Ka	54.1	50.1	-7.4	139	0	0	81.6	78.8	-3.4
30. Sanli	58.0	54.3	-6.4	136	0	0	80.9	68.7	-15.1
31. Taner	59.6	56.4	-5.4	140	0	4	89.8	82.5	-8.1
32. Topkapi	62.4	58.8	-5.8	139	0	0	82.0	75.5	-7.9
33. Tosunbey	57.9	53.2	-8.1	136	0	1	80.3	76.2	-5.1
34. Yavuz	61.3	62.1	+1.3	139	0	0	81.1	78.3	-3.5
35. Zlatoglava	58.6	57.9	-1.2	139	0	2	76.4	72.3	-5.4
Mean	59.3	56.0	-5.4	138.1	0	1.00	77.3	72.7	-5.8
F	**	**					**	**	
CV (%)	4.3	3.9					3.9	3.0	
HSD	8.3	7.1					9.8	7.2	

[1] Total number of white heads observed in all replications, CV Coefficient of variation, ** Significant at $p < 0.01$, C Control, FI Fungus-infected, DCC Decrease in chlorophyll content, LPH Loss of plant height, HSD Tukey's honest significant difference ($\alpha = 0.05$)

Discussion

This study showed that FCR disease is an important risk factor for wheat. These negative effects occur not only through the primary impact of the infection, but also through its secondary effects on plant physiology. Crown rot disease caused by *F. culmorum* leads to infections of varying severity and tissue necrosis in wheat, and the resulting damage disrupts the plant's uptake and transport of water and nutrients. No difference was observed between the control and fungus-infected plots in the number of days to heading, which is a physiological trait. After inoculation, the development of infection and metabolic disturbances in the plant depends on time and environmental factors. The number of days to heading is influenced by biotic and abiotic environmental factors, primarily by genetic structure [49]. That the 35 cultivars used in the study had average number of days to heading of 126.9 and 138.1 days under Yerköy and Yozgat conditions, respectively, demonstrates also the effect of environmental conditions. Chekali et al. [23] reported

Table 7 Effects of crown rot disease on grain yield per plant and disease severity of cultivars in the pot experiment

Cultivar	Grain yield per plant			Severity of disease (%)
	C (g plant^{-1})	FI (g plant^{-1})	LGY (%)	
1. Adali	3.236	2.637	-18.5	56.9
2. Ahmetaga	3.155	3.108	-1.5	50.7
3. Alp 1	3.652	3.505	-4.0	40.0
4. Ayten Abla	4.765	4.328	-9.2	68.0
5. Bagira	5.514	4.578	-17.0	42.7
6. Bayraktar 2000	3.800	3.772	-0.7	65.5
7. Comert 2	3.573	2.653	-25.7	60.0
8. Destan	3.923	3.996	+1.9	66.7
9. Ekiz	4.530	4.401	-2.9	37.3
10. Enola	4.662	4.106	-11.9	34.4
11. Esperia	3.773	4.021	+6.6	24.6
12. Flamura 85	3.785	2.104	-44.4	52.0
13. Glosa	3.925	4.003	+2.0	22.7
14. Halis	4.202	4.063	-3.3	49.2
15. Ikizce 96	3.364	3.170	-5.8	60.0
16. Kenanbey	3.517	2.897	-17.6	61.5
17. Konya 2002	5.824	5.761	-1.1	55.6
18. Krasunia Odes'Ka	4.421	4.531	+2.5	53.8
19. Lucilla	3.094	3.293	+6.4	30.8
20. Maden	3.454	3.626	+5.0	16.4
21. Meke	4.232	4.040	-4.5	28.0
22. Michelangelo	3.803	3.279	-13.8	36.9
23. NE06545	4.430	4.272	-3.6	67.5
24. Nogal	4.201	4.062	-3.3	36.9
25. Rebelde	4.571	4.673	+2.2	24.3
26. Reis	3.732	3.824	+2.5	46.7
27. Rumeli	4.092	3.849	-5.9	30.0
28. Selamibey	4.460	3.990	-10.5	33.3
29. Syrena Odes'Ka	4.264	3.436	-19.4	62.2
30. Sanli	3.383	3.412	+0.8	40.0
31. Taner	3.025	2.318	-23.3	82.7
32. Topkapi	4.348	4.070	-6.4	53.8
33. Tosunbey	2.698	2.321	-14.0	60.0
34. Yavuz	4.220	3.921	-7.1	45.0
35. Zlatoglava	4.812	3.577	-25.7	73.0
Mean	4.013	3.703	-7.8	47.7
F	**	**		
CV (%)	16.7	18.6		
HSD	2.1824	2.2509		

CV Coefficient of variation, ** Significant at $p < 0.01$, C Control, FI Fungus-infected, LGY Loss of grain yield, HSD Tukey's honest significant difference ($\alpha = 0.05$)

no significant correlation between the severity of root and crown rot disease and heading date under semi-arid conditions, which supports our findings. Pathogens that cause root and crown rot attack different parts of the plant at different growth stages [50]; consequently, exposure to infection during early or late periods may also affect the plant's response time. The number of days to heading is defined in the method established by UPOV [48] as the period when the first spikelets appear in 50% of the spikes in the test plot. Considering this method, since the plot contains both healthy and variably infected plants, differences in heading time cannot be directly attributed to the disease. Therefore, a more specific study is needed to investigate this trait.

In this study, *F. culmorum* inoculation was performed first on the seed and then on the plants after stem elongation (Zadoks decimal code 35). In the first count, the number of plants emerging in plots subjected to inoculation (73.7%) was significantly lower compared to the control (81.4%). This reduction was most pronounced in the cv. Flamura 85. The susceptibility of Flamura 85 to root and crown rot disease was previously reported by Özdamar and Özer [51] and Başer et al. [52]. The reduction in plant number continued in the second count after winter; however, this decrease may have resulted from the effects of winter conditions, fungal infection, or a possible interaction between them. The average number of plants in the cultivars inoculated with fungi decreased by up to 63.2%, due to both biotic and abiotic environmental factors. The most important component related to yield in wheat is the number of spikes per square meter [53, 54]. Prescott et al. [50] reported that early infections of root and crown rot disease cause seedling collapse before or after emergence. Infection during emergence and seedling stages caused a reduction in yield due to the direct effect of losses in plant density per unit area.

Plant height is influenced by genetic and environmental factors [55, 56]. Wheat genotypes with high plant height under natural rainfall conditions generally have higher grain yields under drought stress. Therefore, plant height is used as a selection criterion in wheat breeding programs for arid and semi-arid conditions [57]. Fungal infection reduced the plant height of wheat cultivars, decreasing from an average of 67.9 cm in the control to 63.6 cm in the fungus-inoculated plots. Under drought stress, biotic stress factors such as crown rot can lead to reduced plant height and indirectly loss in grain yield. Ahmadi et al. [58] determined a decrease in plant height under water stress conditions, reporting that inoculation with *F. culmorum* had no effect on plant height unless combined with water stress. In contrast, Ozdemir et al. [59] found a strong relationship between infection severity and plant height, and even determined that *F. culmorum* has a greater effect on plant height than F. *pseudograminearum* and is more virulent. Hajihassani et al. [60] investigated the effects of *Pratylenchus thornei* and *Fusarium culmorum* on wheat and determined that both factors reduced plant height. Aktaş [56] examined the agro-morphological characteristics of different cultivars of bread wheat registered in Türkiye and determined their average plant height to be between 80.8 and 151.0 cm. In this study, the fact that the average plant

Table 8 Effect of crown rot disease severity on standardized grain yield of per spike in pot experiment (g)

Cultivar	Severity of disease						Mean
	0	1	2	3	4	5	
Comert 2	1.309	0.942	0.993	1.121	1.042	0.829	1.039 c
Ikizce 96	1.508	1.506	1.372	1.441	1.453	1.295	1.429 a
Reis	1.489	1.326	1.456	1.572	1.505	1.304	1.442 a
Taner	1.591	1.399	1.351	1.119	1.153	0.380	1.166 b
Zlatoglava	1.692	1.478	1.612	1.529	1.371	0.589	1.379 a
Mean	1.518 A	1.330 B	1.357 B	1.356 B	1.305 B	0.879 C	1.291
Loss (%)	0	-12.4	-10.6	-10.6	-14.0	-42.1	

Coefficient of variation: 13.5, Tukey's honest significant difference ($HSD_{\alpha:0.05}$) for disease severity: 0.189, Tukey's honest significant difference ($HSD_{\alpha:0.05}$) for cultivars: 0.165, $HSD_{\alpha:0.05}$ for cultivar× disease severity: 0.101

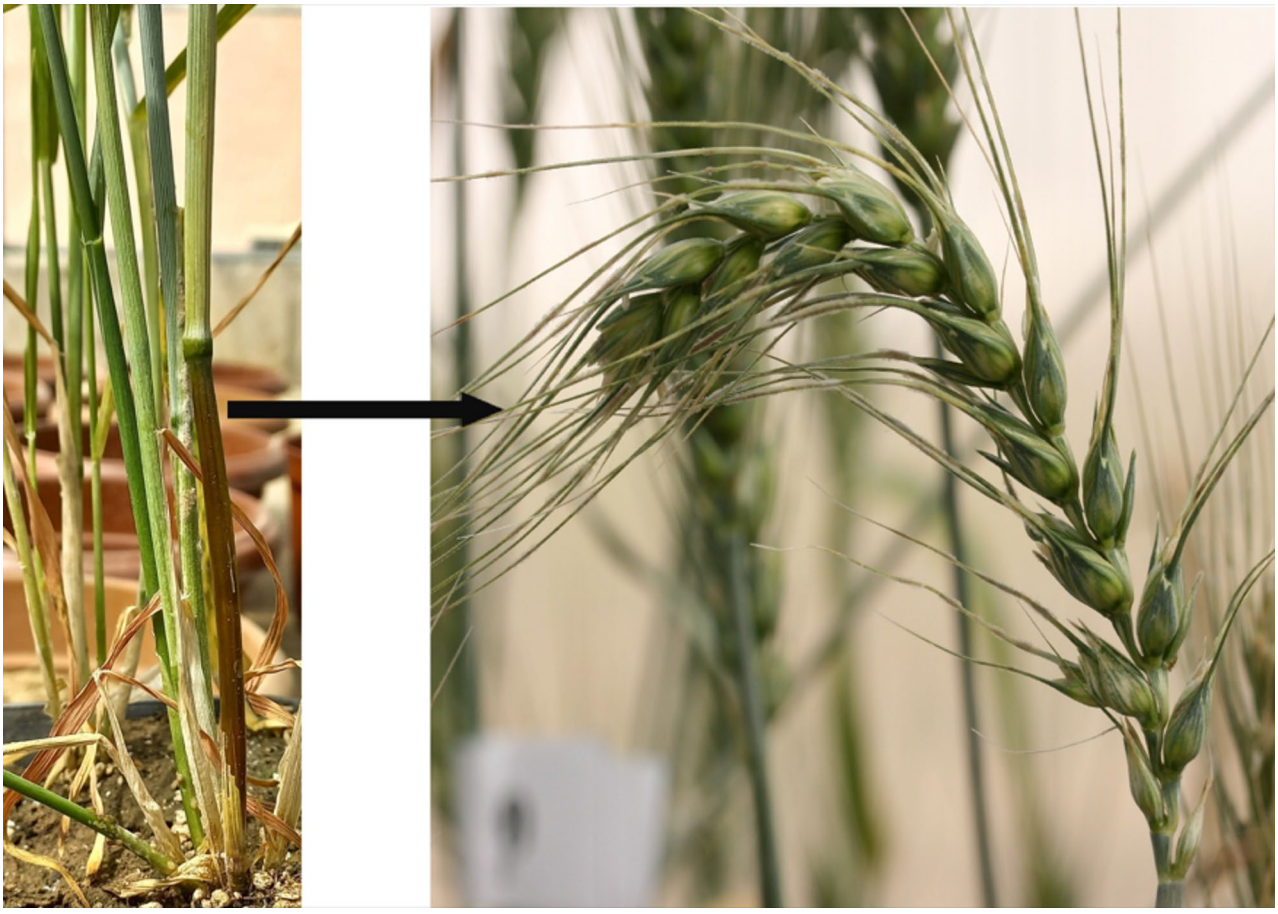


Fig. 2 Appearance of plant stem and spike with a disease severity of 5 on the scale in the pot experiment

heights remained at a lower level than in studies involving similar cultivars can be attributed to environmental stress factors. In recent years, as a result of global warming, significant changes in the climate have been experienced throughout Türkiye. However, extreme meteorological data were recorded in both locations during the experiment year. The lowest temperatures ever recorded to date have been recorded in both locations where the experiment was conducted, especially during the spring months. The average temperatures in December, January, and March were significantly above the long-term average (for example in Yerköy, the January average was 10 times higher than the long-term average), while it fell below the long-term average in April (Table 1). The damage or weakening of plants as a result of encountering such abiotic stress conditions may have caused the infection to progress more easily and increase in severity. As with plant height, the chlorophyll content of flag leaves is also influenced by genotypic and environmental factors [61]. Among environmental factors, plant nutrients are the most influential in chlorophyll content. Crown rot disease caused by *F. culmorum* damages plant tissues

and vascular bundles, causing problems in the transport of water and nutrients [19, 20]. Therefore, fungal inoculation is also expected to have a negative effect on plant chlorophyll content. Chlorophyll content was determined under potted conditions and an average decrease of 5.4% in chlorophyll content was detected in plants inoculated with *F. culmorum*. This finding is consistent with Ahmadi et al. [58], who reported that the chlorophyll content in bread wheat was negatively affected by the *F. culmorum* inoculation.

Under field conditions, disease severity among cultivars ranged from 6.3 to 54.2%, with the average of 29.7%. In the pot experiment, cultivars showed disease severity ranging from 16.4 to 82.7%, with the average of 47.7%. The disease severity level is quite high in the pot experiment compared to field conditions. The high severity of disease under pot conditions can be resulted by the significantly lower number of plants observed in the pot experiment. On the other hand, the sterilization of the potting soil may have removed microbiological competition, allowing *F. culmorum* to multiply faster and enhance its impact. Additionally, in the pot experiment, the fungus may have found more optimal conditions for its growth. Erginbas-Orakci et al. [45] investigated inoculation methods to accelerate the identification and development of wheat varieties resistant to crown rot. Although they found disease severity to be higher in the seedling dipping method, they reported that inoculation using the colonized grain method also produced sufficient disease severity in greenhouse pot conditions. The observed disease severities did not cause the same level of yield loss in the field and pot experiments. The relative effect of disease severity on yield loss was higher under field conditions. Indeed, under field and pot conditions, the average disease severity was 29.7% and 47.7%, while the yield loss was 17.9% and 7.8%, respectively. It is thought that this result was caused by the plants being exposed to less stressful conditions in the pot trial than in the field trial, particularly water stress. Additionally, in the pot trial, the plants were threshed individually by hand, while in the field trial, a threshing machine was used. Therefore, the weak and thin grains in the infected plants may have been blown away by the airflow due to their light weight. The standard spike yields under field and pot conditions and at different disease severity levels support this finding (Tables 5 and 7). The overall average spike yield was 0.800 g spike^{-1}, while the average was determined to be 1.291 g spike^{-1}. Under field conditions at disease severity 5, spike yield decreased to 0.260 g spike^{-1}, while in the pot experiment, spike yield was determined to be 0.879 g spike^{-1} at the same disease severity. These results confirm the difference in disease severity and grain yield losses determined between field and pot experiment. Therefore, in the pot experiment, highly infected plants were able to produce higher grain yield as a result of better nutrient uptake and transport, and possibly higher photosynthetic efficiency. Alahmad et al. [62] reported that when water is available during the plant growth period, there is minimal yield loss; when water is limited and the root system cannot access water due to infection, there is maximum yield loss; and when water is limited but the plant's root system and aboveground parts are at optimal levels, there is a low degree of yield loss. Ahmadi et al. [58] investigated the effects of cyst nematode, *F. culmorum*, and drought stress in their study. They reported that when each stress factor was applied separately, it negatively affected yield components, but when stress factors were applied together, the loss in yield components reached much higher levels.

Thousand- kernel weight is one of the yield components in wheat and is also an important physical quality indicator [14, 63]. The thousand-kernel weight loss caused by crown rot is significant because it has negative effects on both yield and quality characteristics. Under field conditions, an average reduction of 5.3% in thousand kernel weight was recorded in the cultivars subjected to fungal infection (Table 4). Stress conditions, particularly during flowering and grain filling, increase the severity of infection. As a result, disruptions in the transport of water and nutrients reach their highest level, causing a shriveled grain structure and a decrease in test weight, which is one of the quality indicators in trade. This situation ultimately leads to income loss for growers [64, 65]. Alahmad et al. [62] determined the average thousand-kernel weight to be 37.7 g in the presence of crown rot disease and 41.9 g in the absence of infection, revealing the decrease in thousand-kernel weight caused by crown rot disease. Similarly, a 5.3% loss in thousand-kernel weight was determined when fungal inoculation was performed in this study. Abdallah-Nekache et al. [66] reported that the effect of *F. culmorum* on thousand-kernel weight was much higher than that of *F. pseudograminearum*, with a loss rate ranging from 22.6 to 36.3%.

Fusarium-induced crown rot disease causes a reduction in spike yield [58]. In this study, disease severity was determined and classified according to the symptoms observed on plant stems. And standardized spike yield was used to enable a more objective comparison among spikes belonging to different severity classes (Tables 5 and 7). Under field conditions, the standardized yield of infected spikes decreased significantly depending on disease severity. However, the degree of decrease varied among cultivars. Genotypes may exhibit different translocation abilities under stress conditions [67, 68]. The growth stage at which the plant was infected, the severity of the fungal attack, drought, and biotic and abiotic stress conditions caused by other pathogens in the environment may, of course, have contributed to the variability in ear

yield among genotypes. In the field experiment, the average spike yields obtained from labeled plants according to disease severity formed six different statistical groups, whereas in the pot experiment, the averages formed three different statistical groups. This difference between field and pot experiments is thought to be due to the absence of water stress in pot experiments, and the studies by Alahmad et al. [62] and Ahmadi et al. [58] support this finding.

These general observations were also valid when the cultivars were examined individually. In the cv. Esperia, disease severity was determined to be 6.3%, and yield loss remained at 2.0%. In contrast, although a relatively high disease severity of 48.7% was observed in the cv. Glosa, the yield loss was determined to be 19.1%. These results indicate that, as a disease management strategy, priority should first be given to the selection of high-yielding cultivars, followed by those that are tolerant to disease severity.

Conclusion

The increase in biotic stress factors in wheat due to climate change poses a serious threat to countries like Türkiye, where wheat is a staple food. This study provides a comprehensive evaluation of the responses of 35 common bread wheat cultivars in Türkiye to *Fusarium culmorum*–induced crown rot under both field conditions in semi-arid environments and in pot experiments. The findings clearly demonstrate that crown rot constitutes a substantial constraint on wheat productivity under the experimental conditions. Fungal inoculation significantly reduced plant establishment, plant height, thousand-kernel weight, chlorophyll content, and ultimately grain yield. Under field conditions, FCR infection caused an average yield loss of 17.9% across the 35 cultivars. Spike yield decreased significantly with increasing disease severity, with an average loss of 77.8% recorded at the highest severity level. Disease severity was higher in pot conditions, but yield losses were lower. This suggests that environmental stress, especially limited water availability, increases the impact of crown rot damage. These findings reinforce the view that disease impact is not solely a function of pathogen virulence but is strongly modulated by environmental factors.

The standardized spike yield, the original output of this study, has emerged as a practical and effective method for determining the susceptibility of cultivars to the disease. This approach allows for the comparison of the responses of a large number of cultivars or the assessment of infection damage across extensive cultivation areas. Standardized spike yield also provides an objective and precise approach for measuring disease-induced physiological stress. The differences observed in disease severity and yield loss among cultivars indicate variations in their levels of resistance. Considering the increasing prevalence of crown rot in Türkiye's major wheat-growing regions under changing climate conditions, the development of resistant cultivars must be integrated with appropriate agricultural practices.

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Authors' contributions
All authors contributed equally to the study design, experimental work, data analysis, interpretation of results, and manuscript preparation.

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Data availability
Data will be available on request to the corresponding authors.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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